



Determining Root Causes of Mysterious Hardware Failures using High Resolution CT Scanning

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Introduction

What is CT Scanning?

- Computed Tomography (CT Scanning) is a process that uses hundreds to thousands of two-dimensional X-ray scans of an object to create a three-dimensional computer model of the item

CT Scanning Method

Example with a Carburetor



X-ray Tube

X-ray tube
illuminates
test object

Object is tilted relative to
the vertical rotation axis



Carburetor

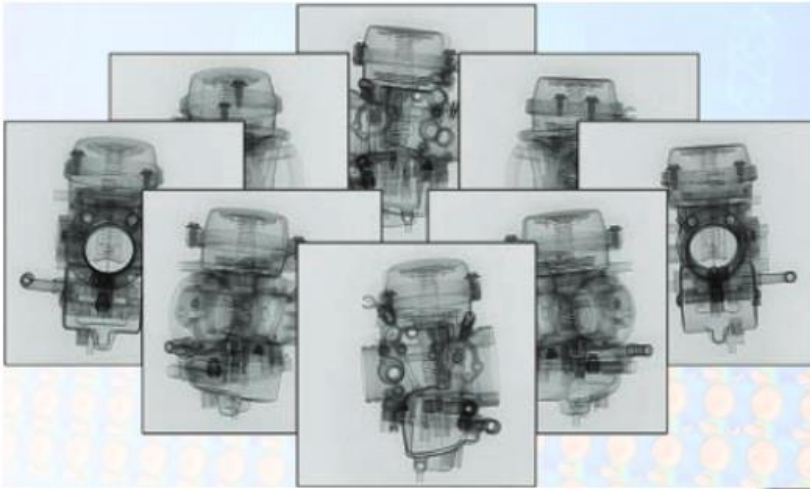
Item being scanned is
rotated slightly after
each image is recorded



Flat Panel
X-ray Detector

2-D images
recorded from
digital detector

CT Scanning Method



Hundreds to thousands of 2-D images are taken, each one at a different rotation angle

Images are combined into a 3-D computer model of the object

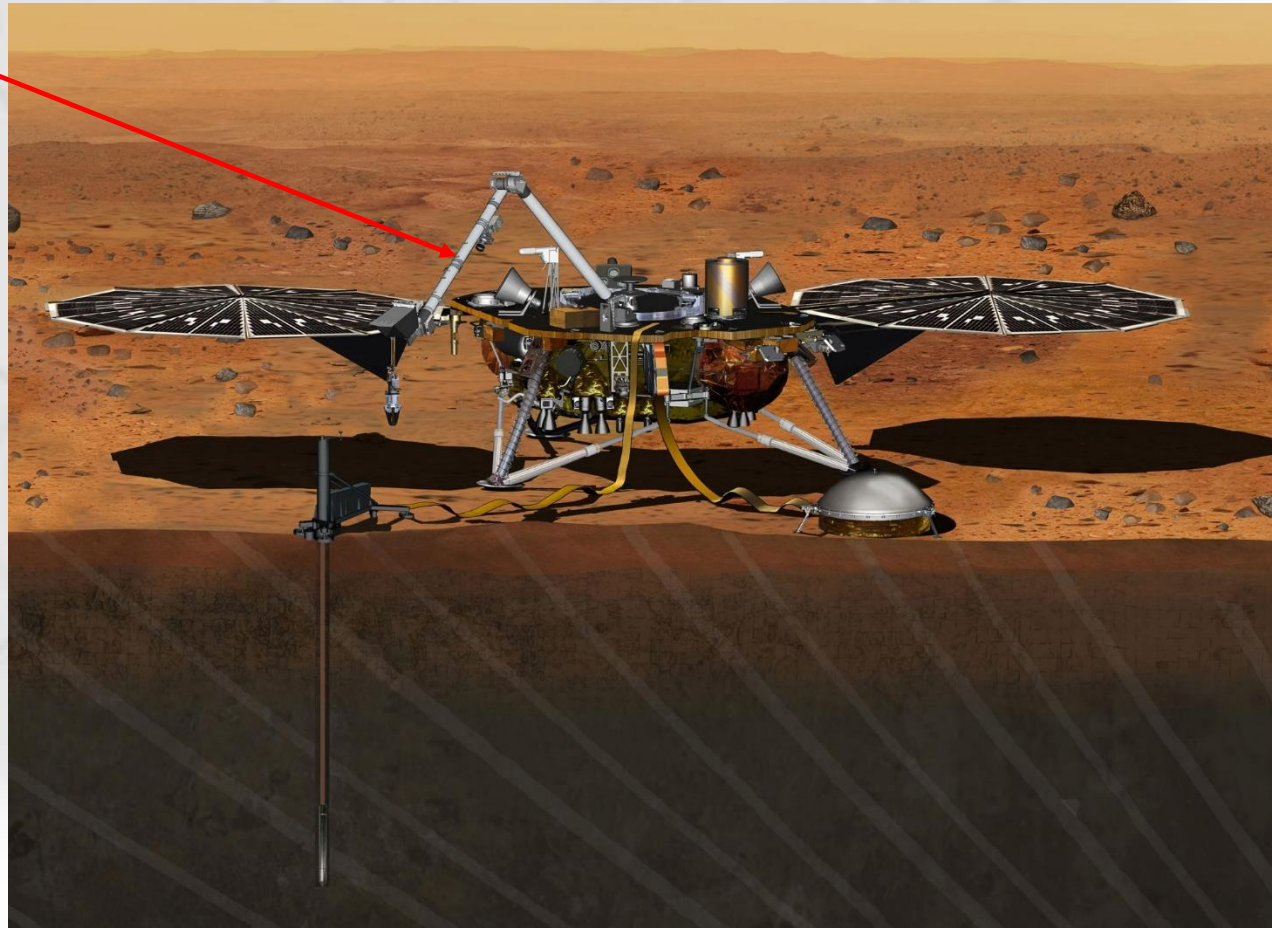


CT Scanning Benefits

- The resulting computer model can be rotated and sectioned just as can be done with a computer design solid model
- A CT scanned model allows one to view and inspect the actual hardware at fine levels of detail within the completed assembly
- Clearances that are otherwise inaccessible can be measured with high precision

Case 1: InSight Mission Motors

- The recently launched InSight mission to Mars has a robotic arm called the Instrument Deployment Arm (IDA)



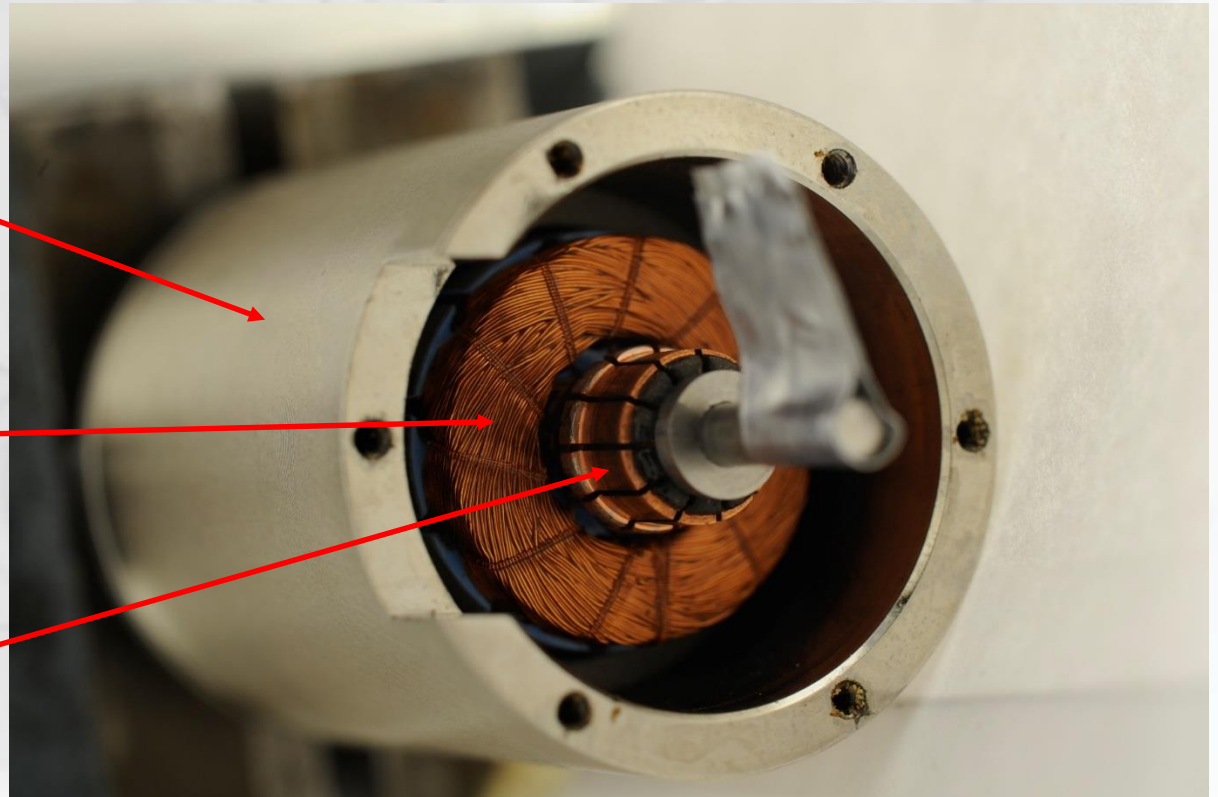
InSight Mission Motors

- The IDA uses permanent magnet brushed motors for operation of the four rotary joints of the arm

Motor Housing

Motor Rotor

Commutator
Assembly



End bell and brush assembly removed in this view

InSight Mission Motors

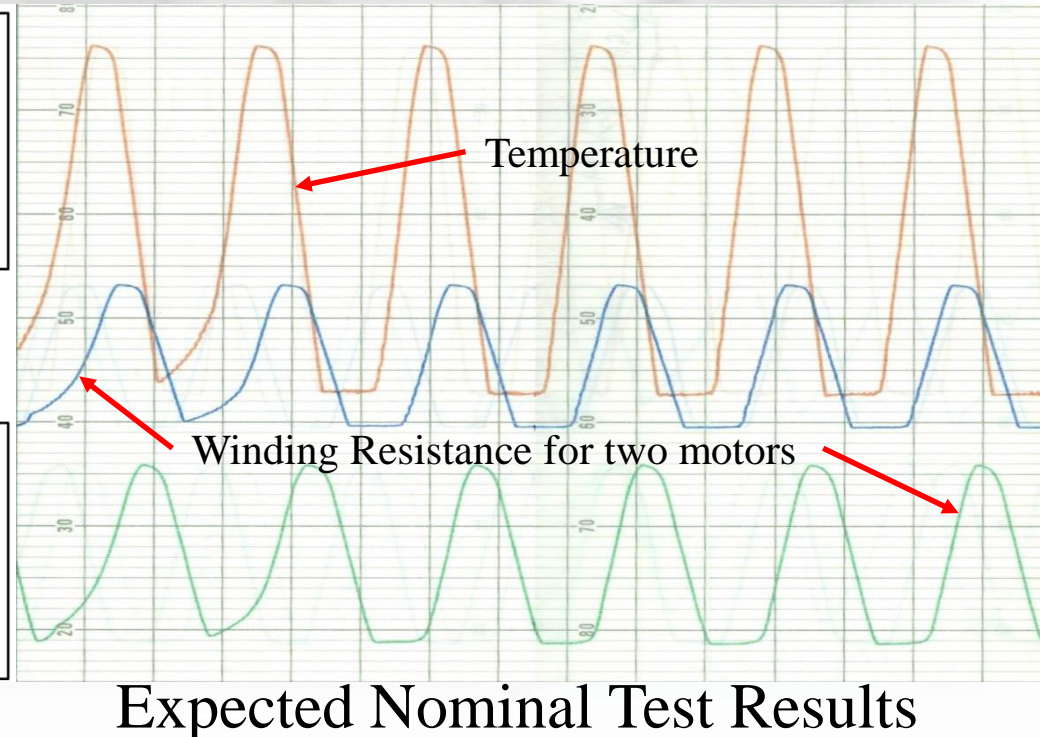
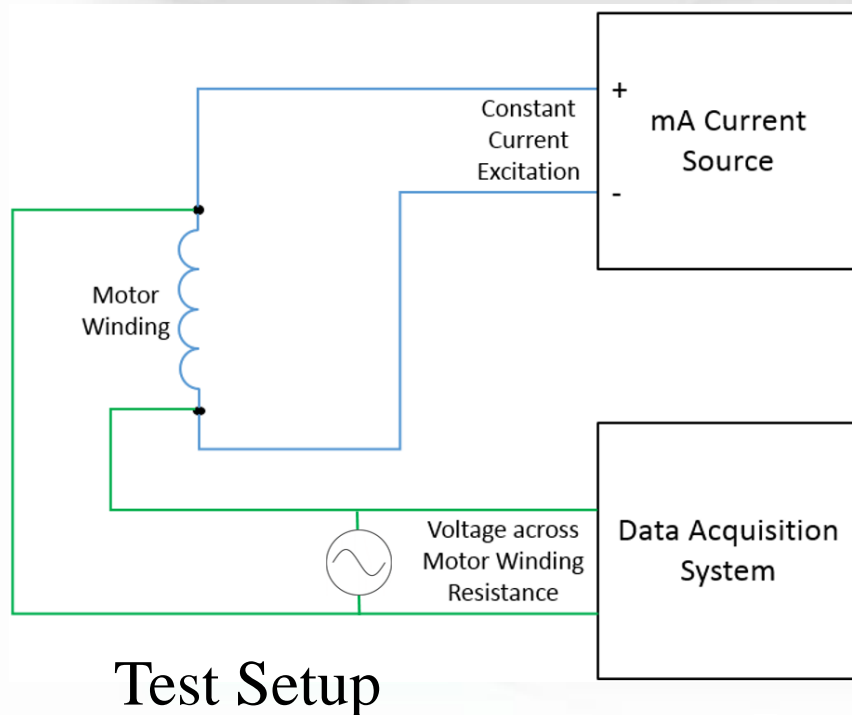
Thermal Cycle Testing

- The IDA motors will be exposed to large thermal cycles during the mission due to the daily variation in temperature of the Mars environment
- Qualification hardware components are thermal cycle tested before delivery to demonstrate adequate thermal cycling margin of the component design
- The IDA motors were subjected to thermal cycle testing while continuously monitoring the health of the motor windings

InSight Mission Motors

Thermal Cycle Test Setup - Monitoring

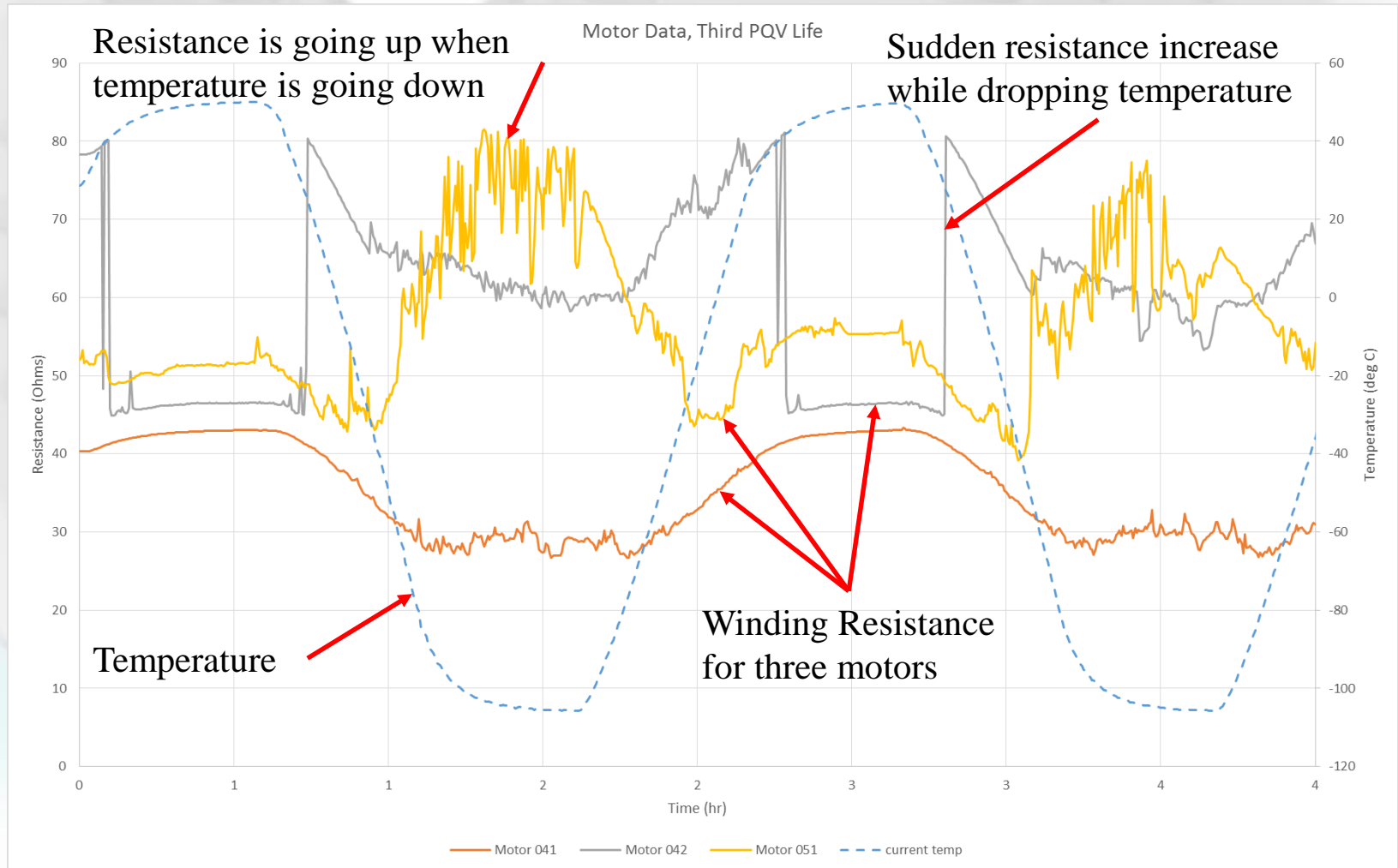
- The winding resistance varies with temperature
- A current source power supply is attached to the windings and the voltage is measured directly



InSight Mission Motors

Thermal Cycle Test Measurements

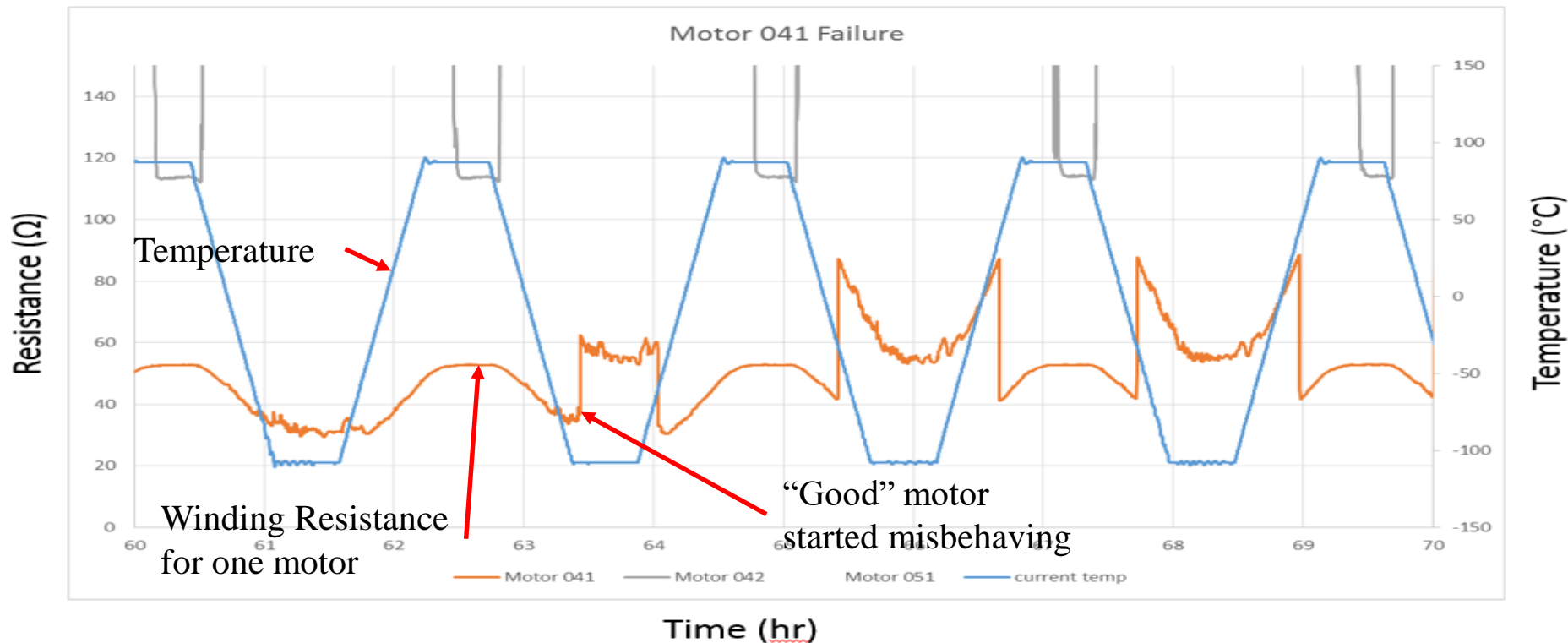
- The test started well, but then . . .



InSight Mission Motors

Thermal Cycle Test Measurements

- It appeared that one motor was behaving, until . . .



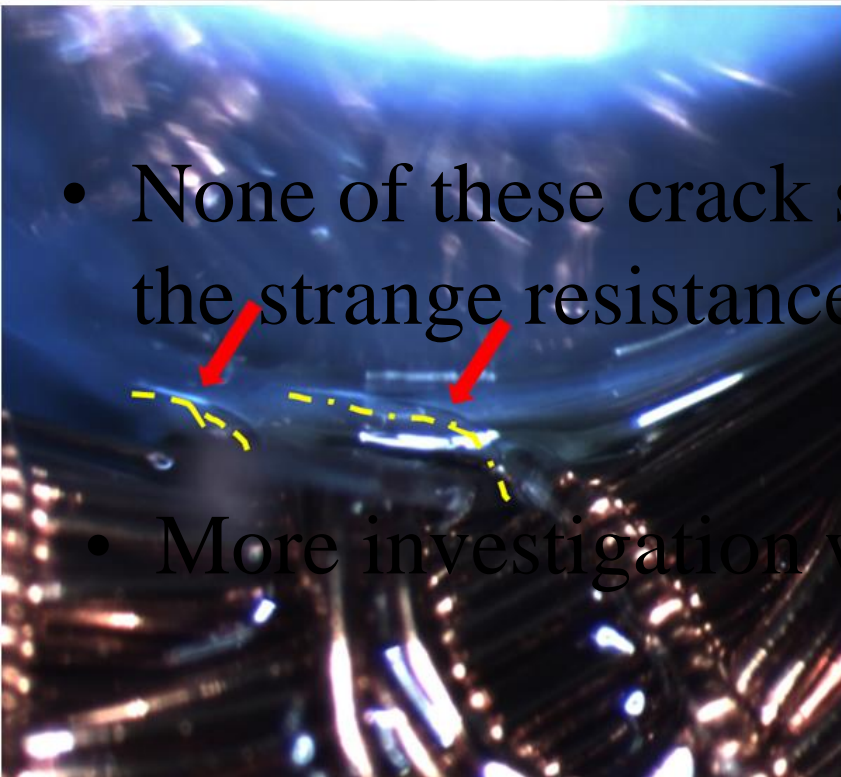
InSight Mission Motors

Looking for the Source . . .

- Inspection of the three motors with an optical microscope revealed the presence of cracks in the epoxy restraining the motor windings

- None of these crack sites revealed the source of the strange resistance changes in the windings

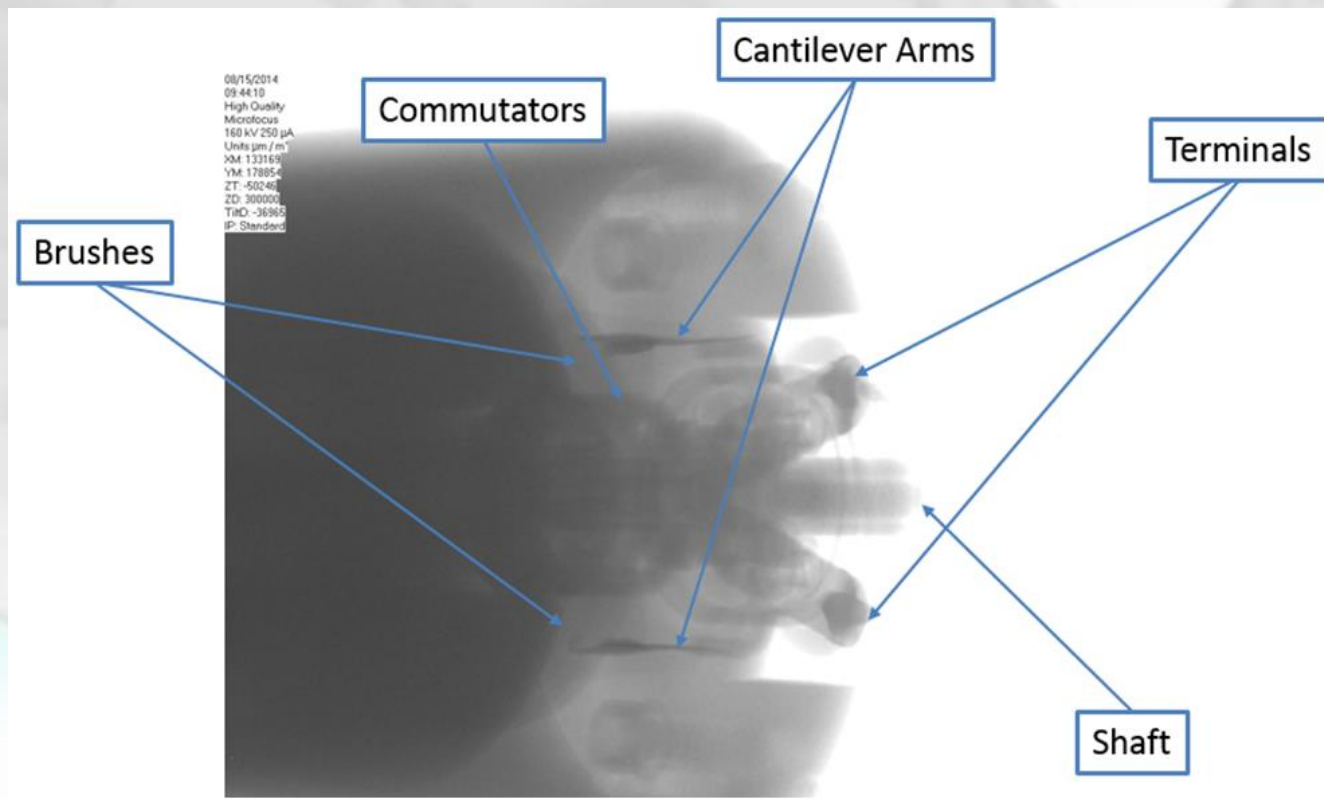
- More investigation was necessary . . .



InSight Mission Motors

Looking for the Source . . .

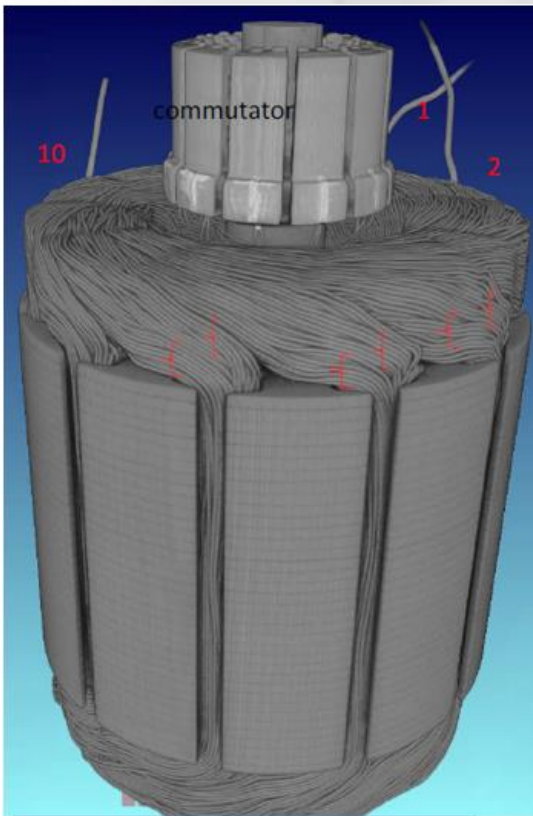
- Standard X-ray inspection revealed nothing useful
- The brushes can be seen to be properly assembled!



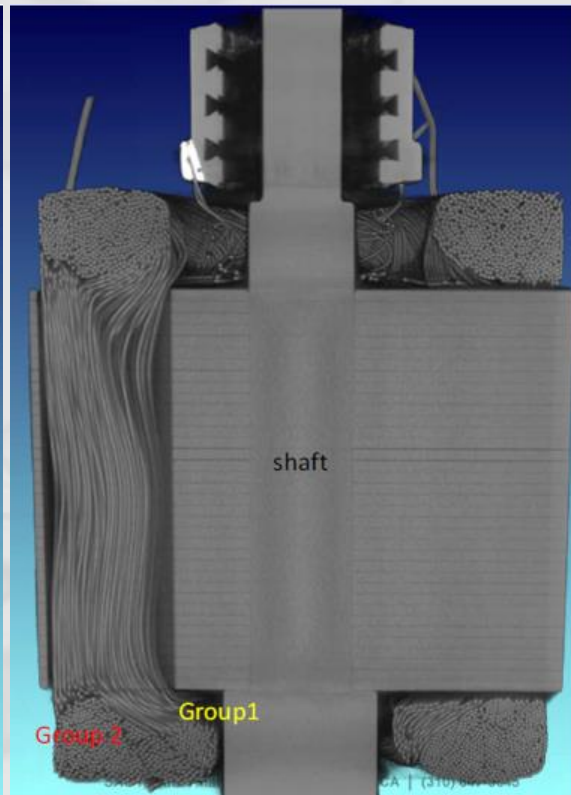
InSight Mission Motors

Looking for the Source . . .

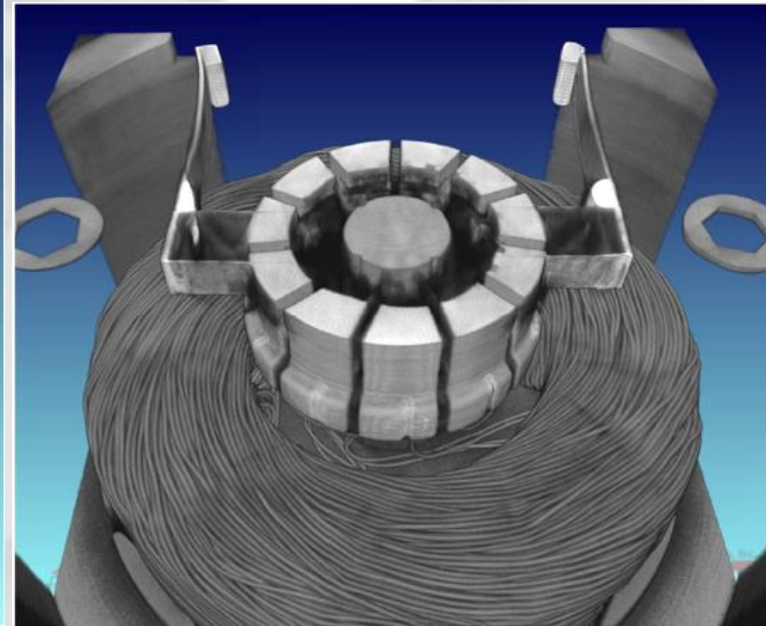
- CT X-ray inspection revealed a great many things!



Rotor Assembly



*Section of Rotor Showing
Wires in the Slot*



*Brushes, Commutator,
and Cantilever Arms*

InSight Mission Motors

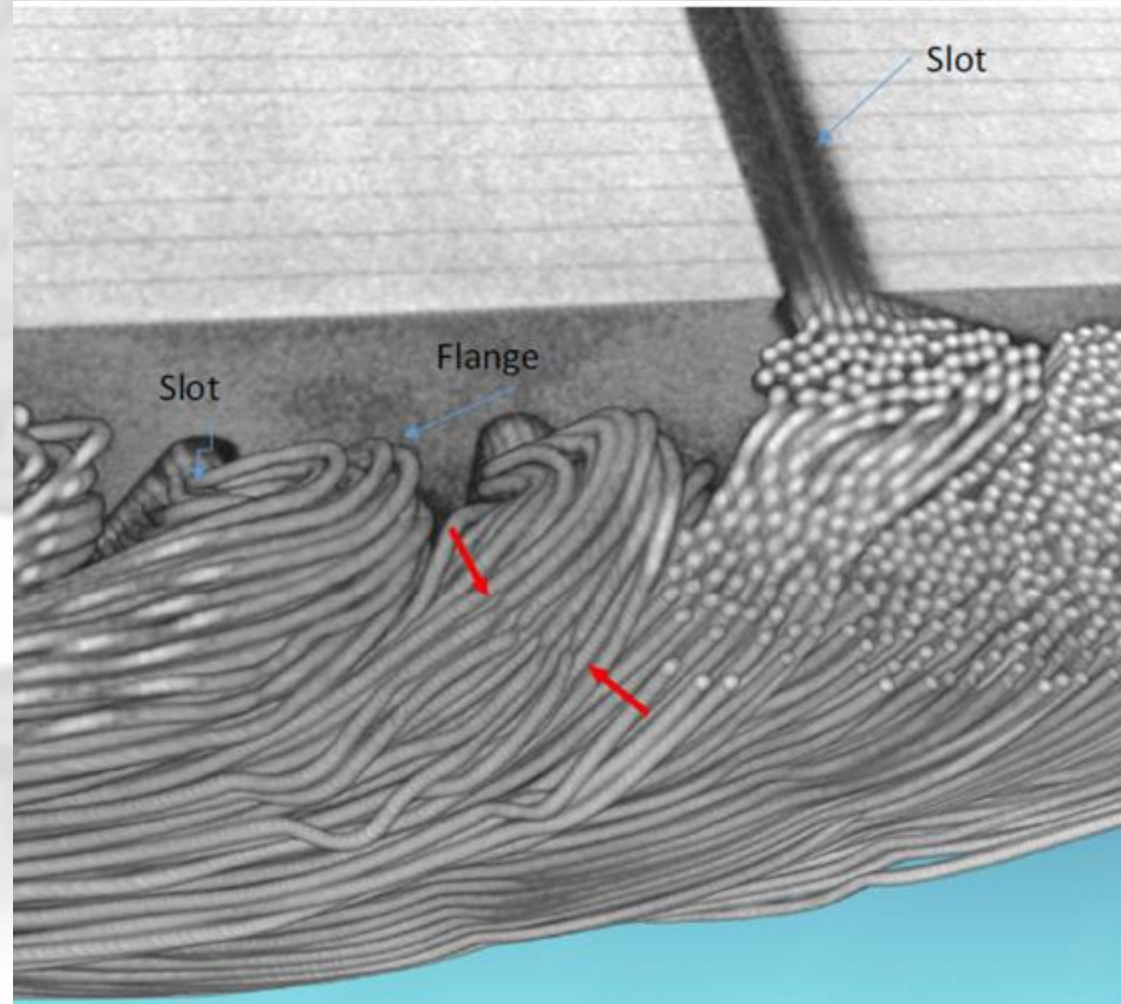
Almost There . . .

- The CT scanned model provides the opportunity to investigate the individual wires within the winding assembly
- The model allowed zooming into the areas where the cracks in the epoxy were identified in the optical inspection
- Wire damage seemed to be apparent at the locations of the cracks in the epoxy

InSight Mission Motors

Almost There . . .

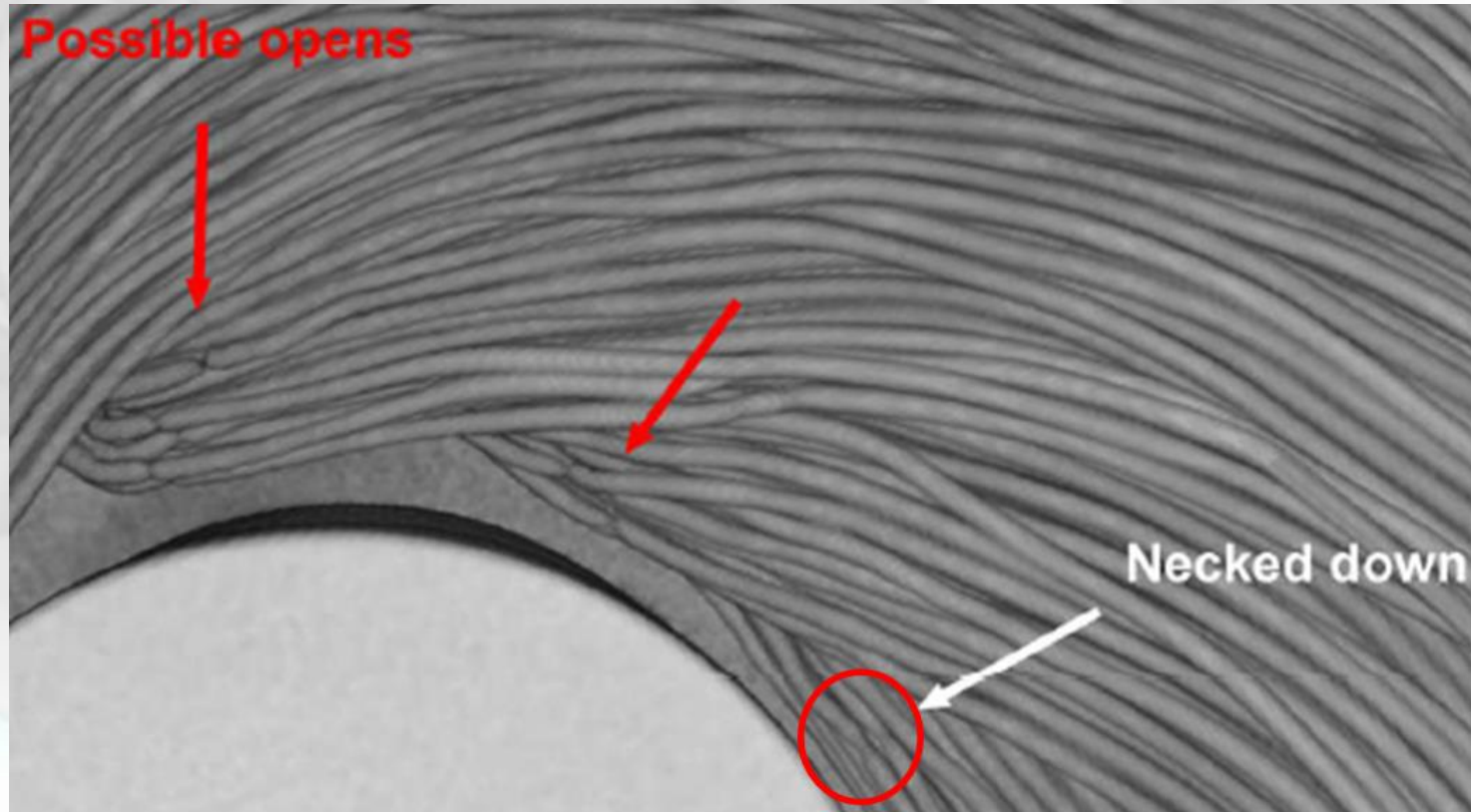
- The arrows indicate possible damage to the winding wires
- The high resolution of the model allowed further magnification of these locations



InSight Mission Motors

The Culprit is Revealed

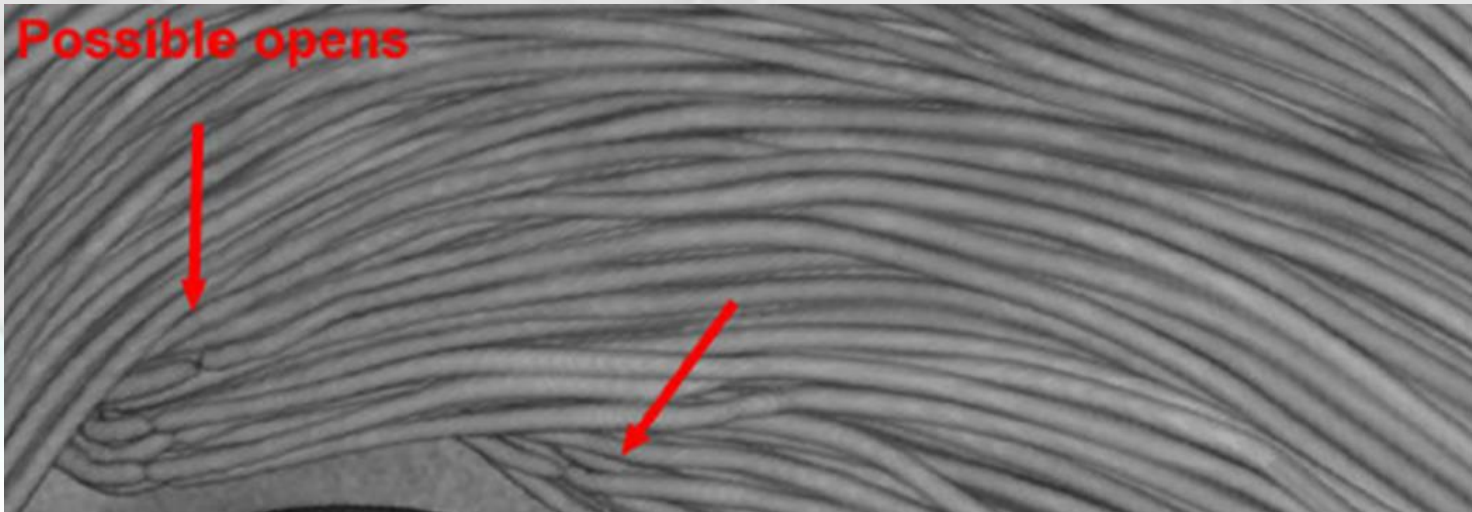
- Breaks in individual wires were detected with reduced cross-sectional area (necked down)
- Other locations showed necked down regions as well



InSight Mission Motors

The Culprit is Revealed

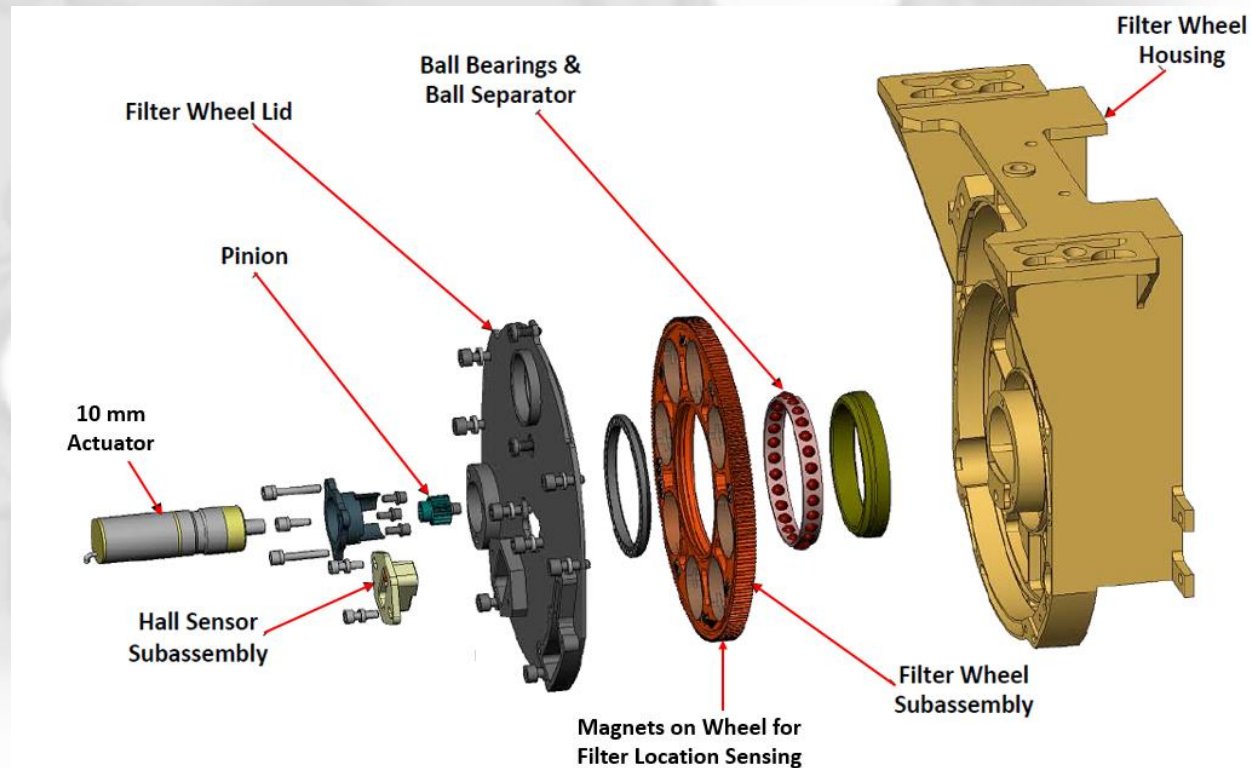
- The reduced cross-sectional area indicated a tensile failure of the wire that is temperature dependent
- The failed regions would re-contact as the temperature was raised, hiding the failure at warmer temperatures



Case 2: Curiosity and Mars 2020 Actuators

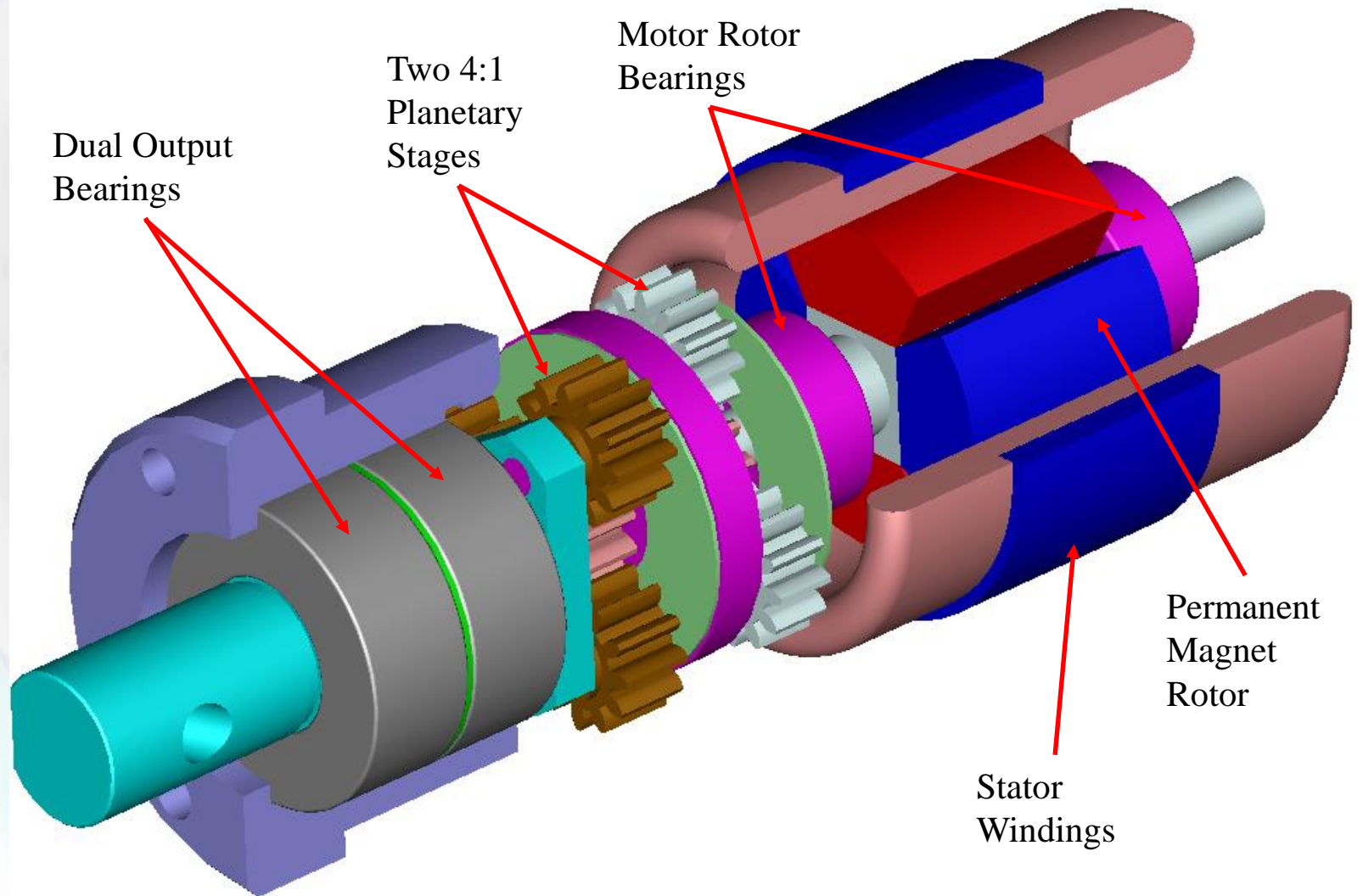
Life Test Actuator

- A 10mm diameter motor/gearbox assembly was tested to failure in a life test
- The unit was driving a filter wheel assembly with a pinion to ring gear configuration



Curiosity and Mars 2020 Actuators

Life Test Actuator Configuration



Curiosity and Mars 2020 Actuators

Test-to-Failure

- The 10mm actuator is a stepper motor with a 16:1 gearbox driving the filter wheel through a pinion/ring gear
- The number of steps between filter positions was monitored and compared to the number of commanded steps
- When the commanded steps was greater than the expected steps, the motor step integrity was lost
- The drive current was increased until step integrity was recaptured

Curiosity and Mars 2020 Actuators

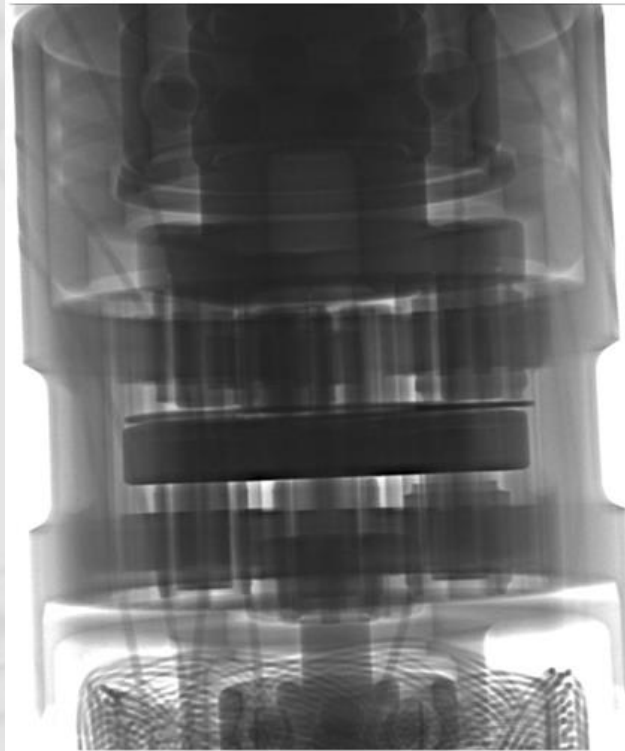
Test-to-Failure

- The motor driver was operated at 20% of its maximum drive current at the start of the life testing
- When the unit demonstrated a loss of step integrity, the drive current was increased to 45% of maximum to resume the step integrity
- The next time step integrity was lost, the drive current was increased to 100%
- When the step integrity was compromised at 100% of the drive current, the test was terminated

Curiosity and Mars 2020 Actuators

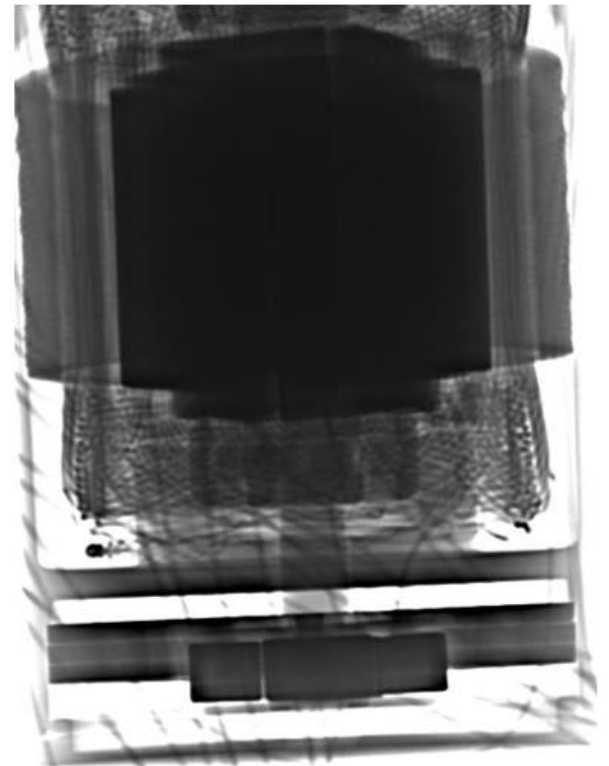
Looking for the Failure Location . . .

- Standard X-ray inspection seemed to indicate the rotor was displaced axially



X-Ray Image Showing the Gearbox Section of the Actuator.

Output Ball Bearings are at the Top of the Image and the Front Motor Bearing is at the Bottom



X-Ray Image Showing the Detent Magnet Section of the Motor Assembly. Magnets are on the Rotor and the Teeth are on the Stator

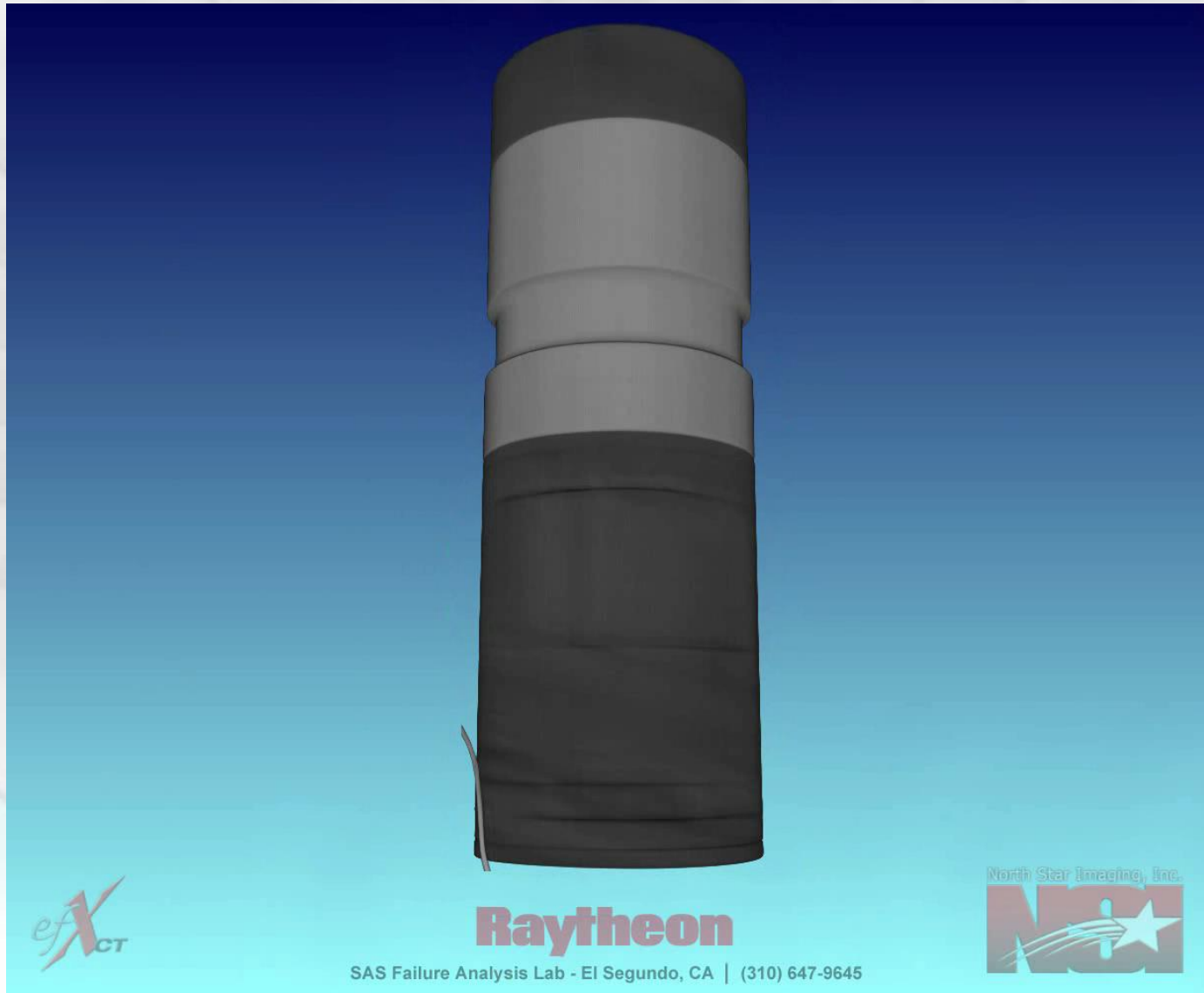
Curiosity and Mars 2020 Actuators

Looking for the Failure Location . . .

- Disassembly of the actuator would require cutting the gearbox and motor apart, possibly losing any failure evidence
- CT Scanning was employed to perform detailed inspection without disturbing the interior of the actuator

Curiosity and Mars 2020 Actuators

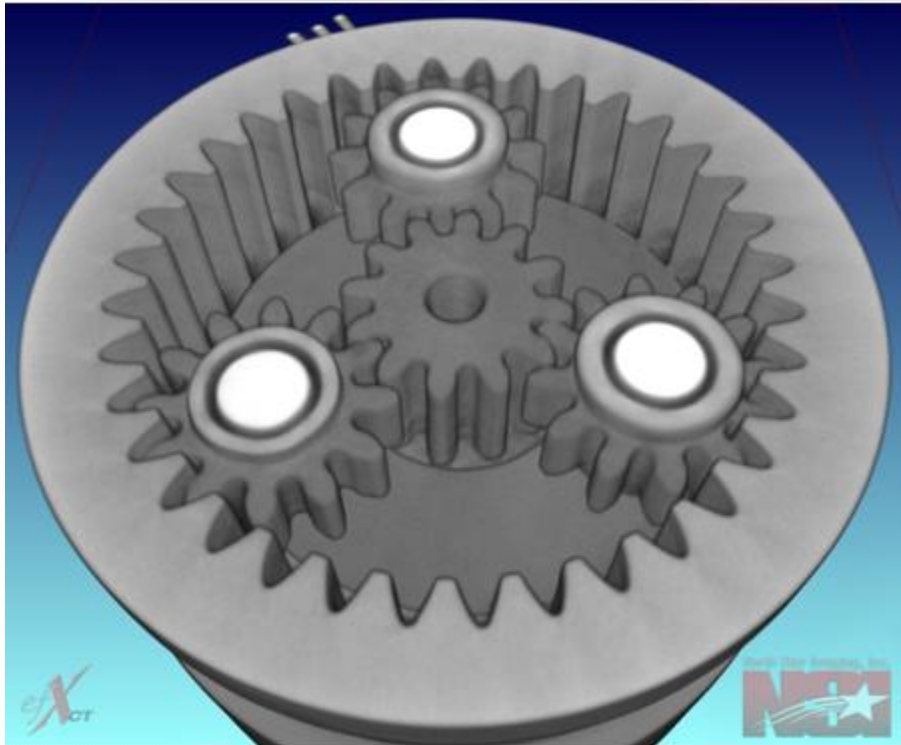
Capability of the CT Scanned Model



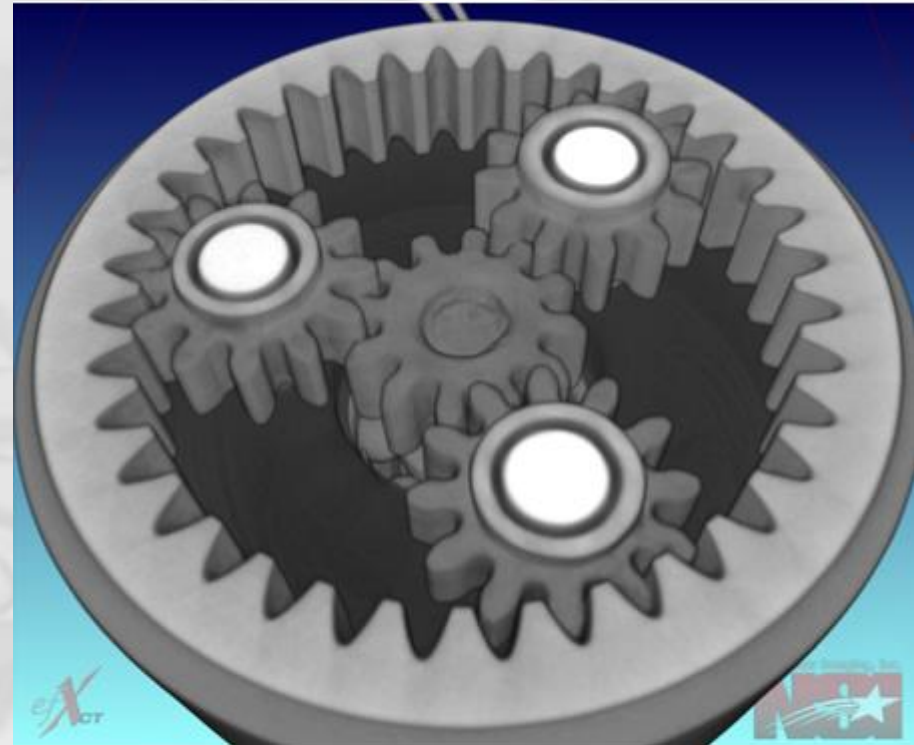
Curiosity and Mars 2020 Actuators

Still Looking . . .

- The gearbox was considered the most likely source of the failure so it was inspected in detail first



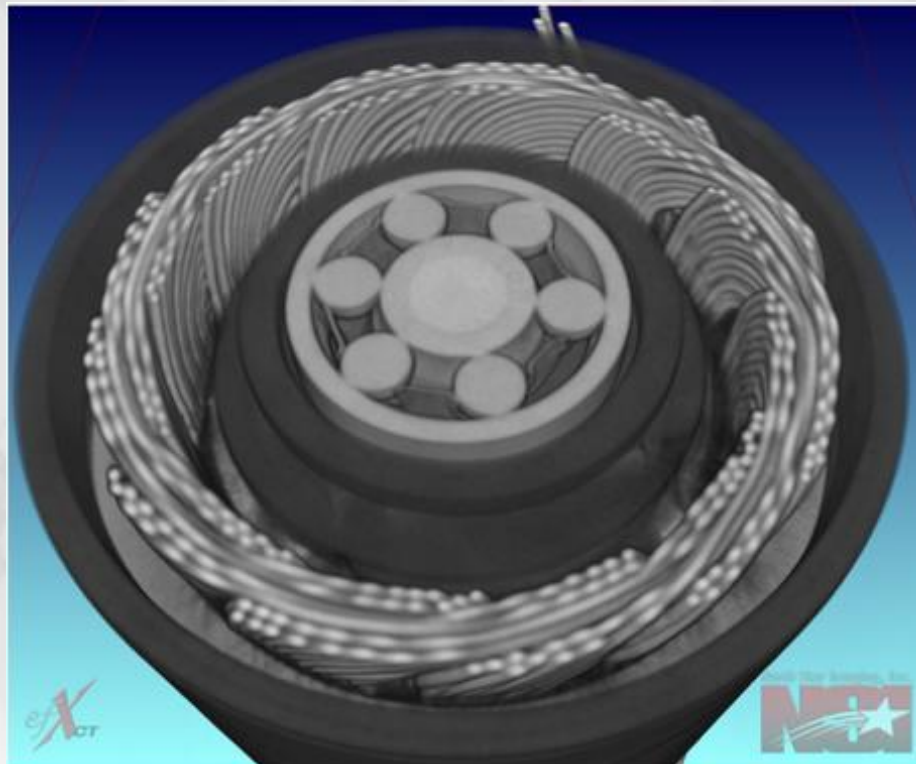
Output Planetary Gear Stage



*Input Planetary Gear Stage with the Motor
Pinion at the Center*

Curiosity and Mars 2020 Actuators Still Looking . . .

- Moving down through the actuator to the output of the motor revealed no failure sources . . .

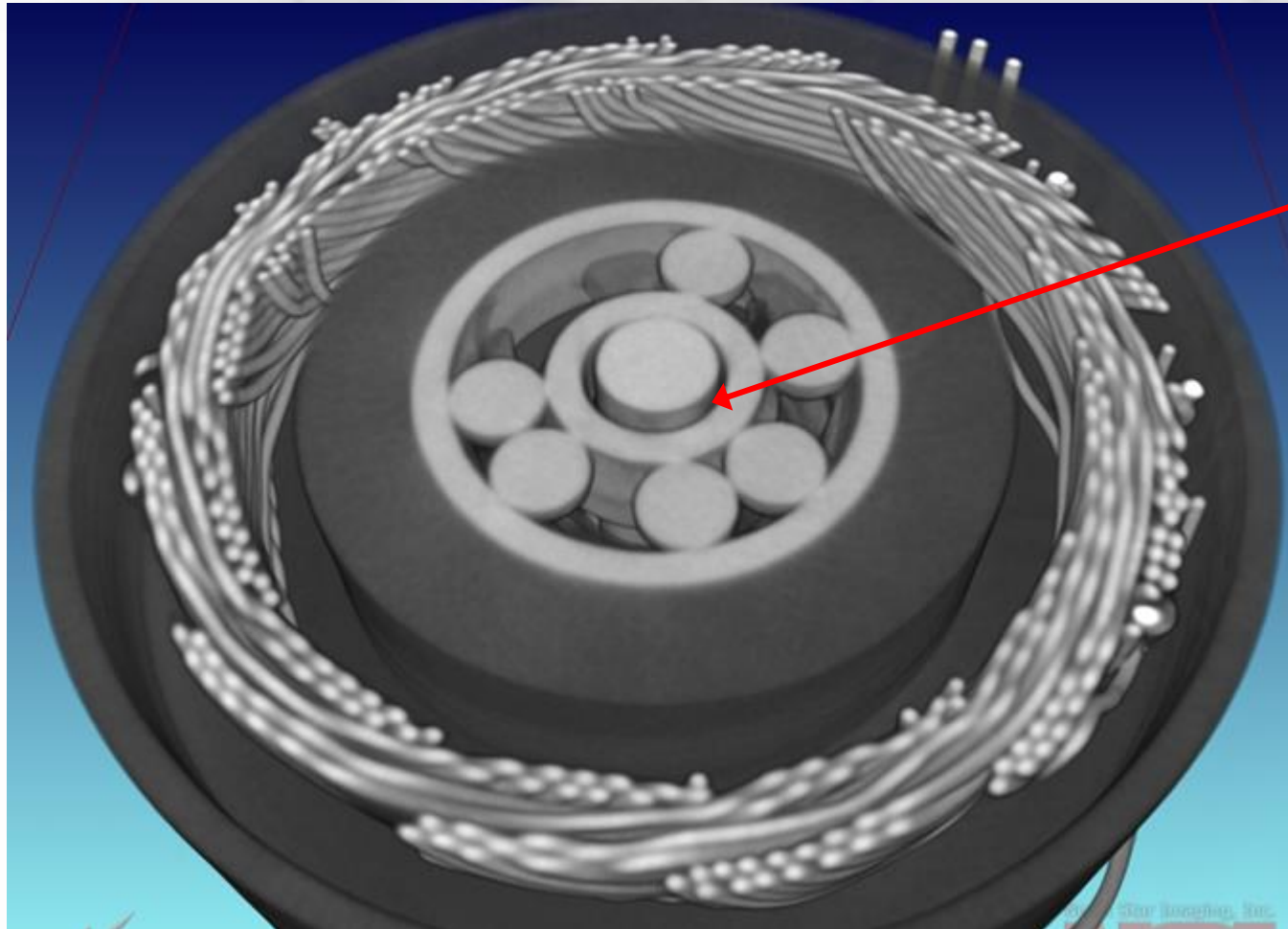


*Front Motor Bearing Closest to the Gearbox
Input*

Curiosity and Mars 2020 Actuators

The Source is Discovered

- Until the motor rear bearing was revealed!

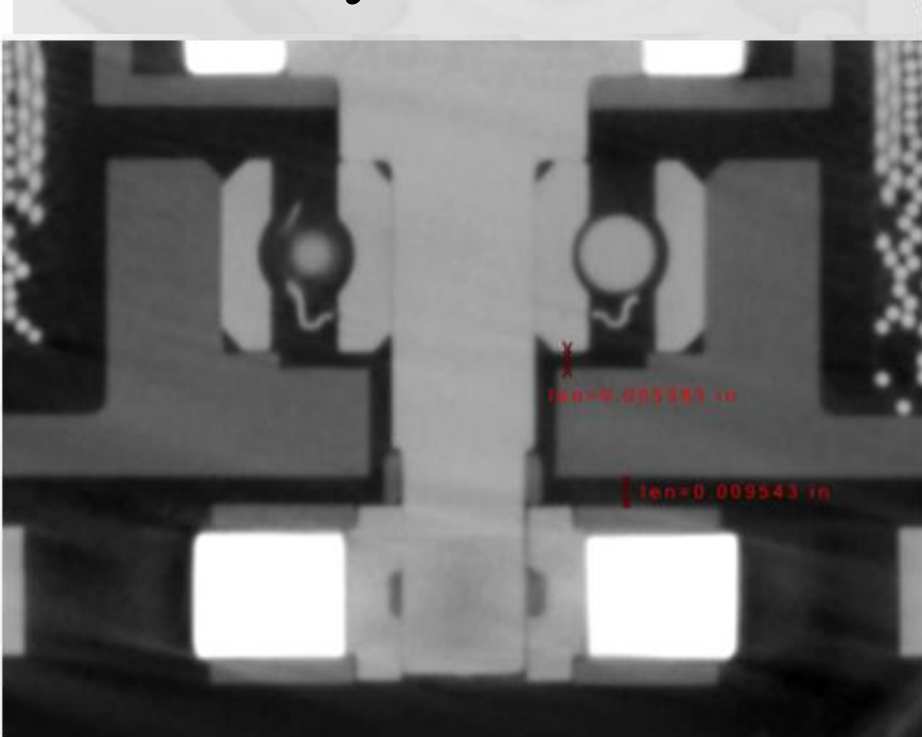


- Notice the fit of the motor shaft to the bearing bore . . .

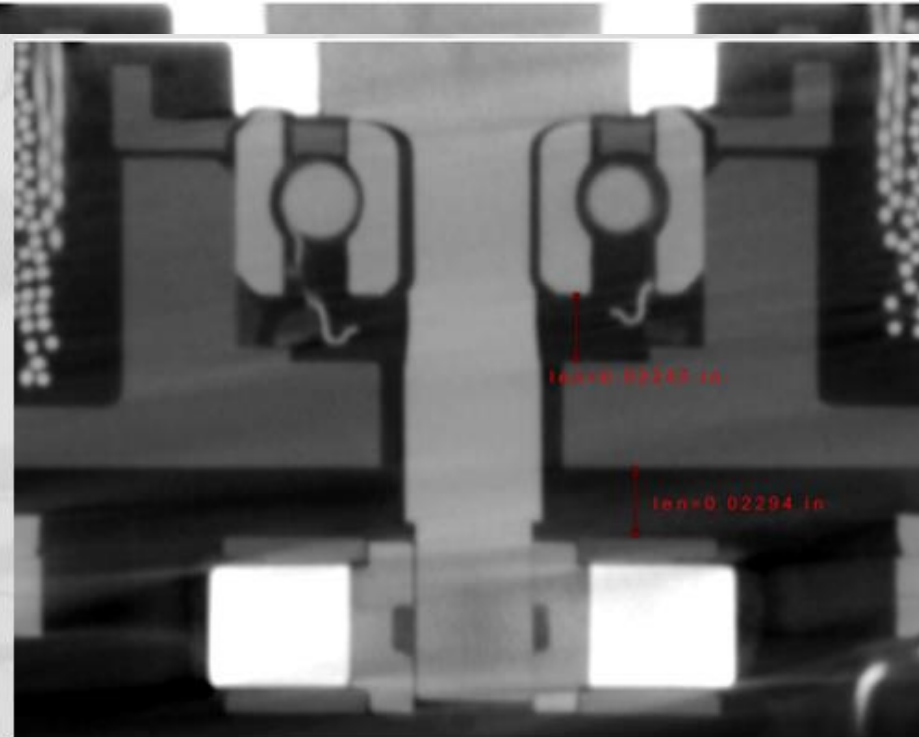
Curiosity and Mars 2020 Actuators

The Source is Discovered

Healthy New Motor of Healthy & Life Test Motors



*Healthy Motor at the Beginning of Life Showing Bearing Placement and Shaft Fit.
The measurements in the images are in inches
(0.0095 in = 241 microns)*



*Life Test Motor Showing Shaft Wear and the Bearing Having Moved Toward the Rotor. The Ball Retainer is Seen Located Under the Bearing Assembly.
(0.0229 in = 582 microns)*

Summary & Conclusions

InSight Motor Windings

- Thermal cycle testing is a crucial test for hardware that will see large temperature swings
- Continuous monitoring of the item being tested is critical – the IDA motor winding failure never appeared at room temperature
- The epoxy cracks were an indicator of a problem but did not expose the failure source
- Destructive inspection may never have found the necked down and broken winding wires, leaving the behavior a mystery forever

Summary & Conclusions

10 mm Actuator Life Test Unit

- The machining required to open the 10 mm actuator would likely have lost the failure evidence or, at best, mixed the evidence with products of the disassembly
- Additionally, the focus of the failure investigation was the motor/gearbox interface prior to the CT scan – which would have led to cutting the assembly apart in the wrong location

Summary & Conclusions

- High Resolution CT Scanning inspection methods provide the ability to interrogate a failure without the risk of losing the failure evidence – a primary tenet in failure analysis

